Magnetic Shielding in Hall Thrusters

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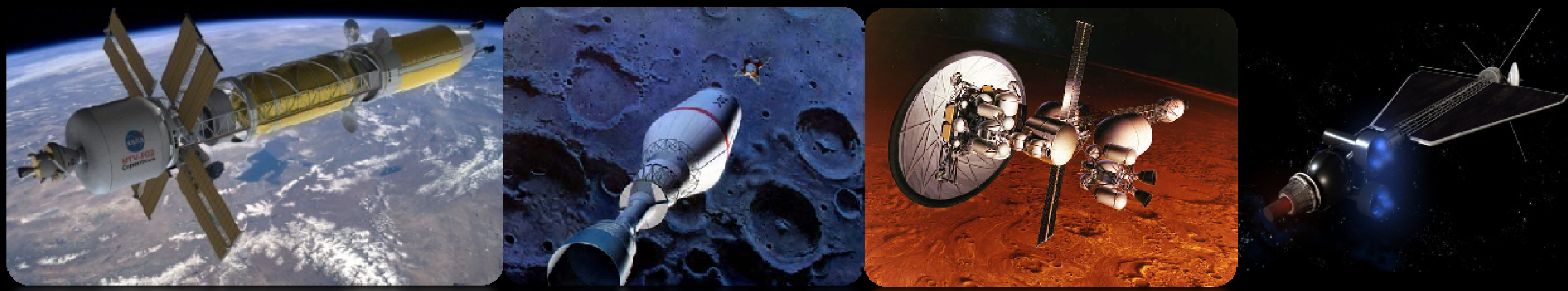
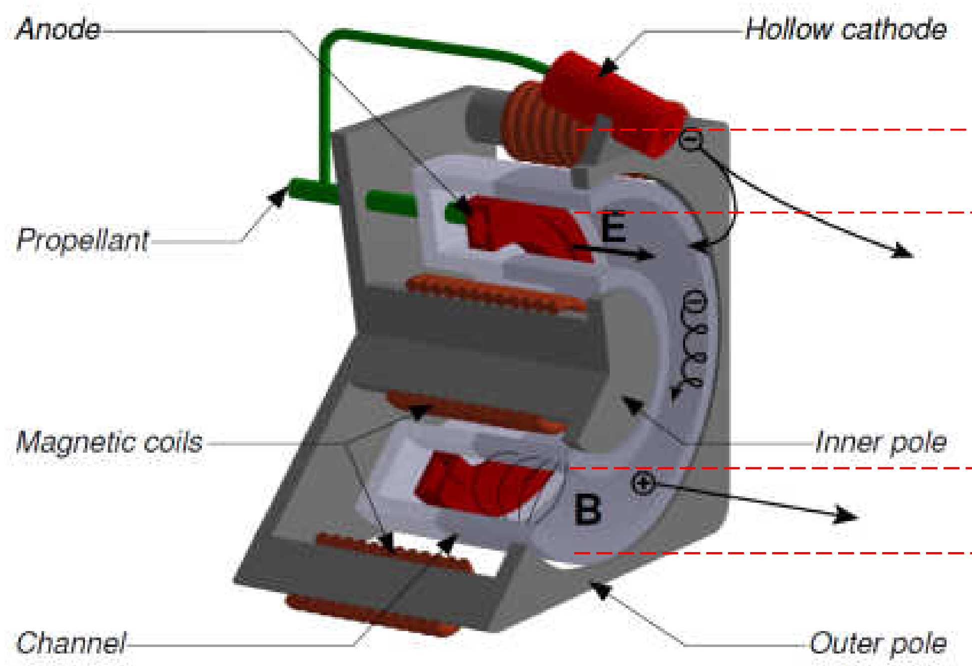
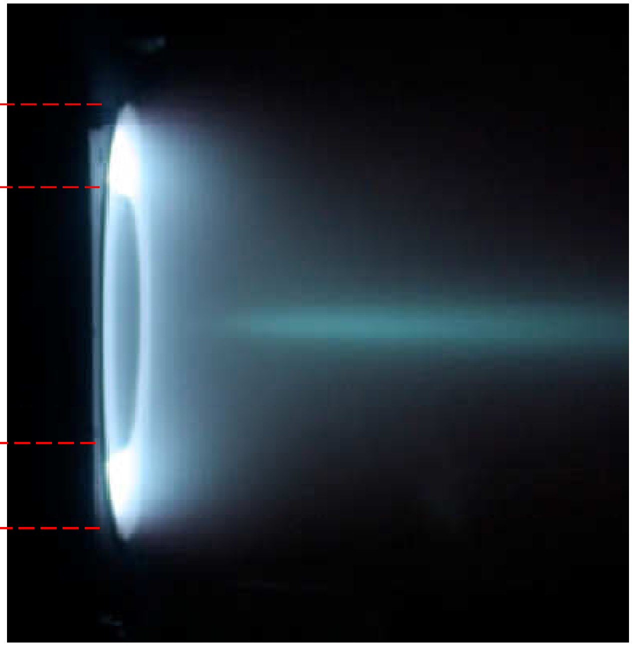
High-power, long-life Hall thrusters are needed for NASA's human exploration missions.



- Motivation
  - At high power levels (>300 kW) solar electric propulsion could significantly reduce the number of heavy lift launch vehicles required for a human mission to a near earth asteroid (2010 NASA HEFT study)
  - High-power Hall thrusters could enable a variety of piloted and cargo missions for NASA in support of human exploration
  - Large amounts of power in space are becoming increasingly available
- NASA's Advanced In-Space Propulsion (AISP) Project is tasked with the development of high-power EP systems for human exploration missions
  - AISP project supports the Enabling Technology Development and Demonstration (ETDD) Program
  - ETDD established by NASA in 2010 to increase the capabilities and reduce the cost of exploration activities

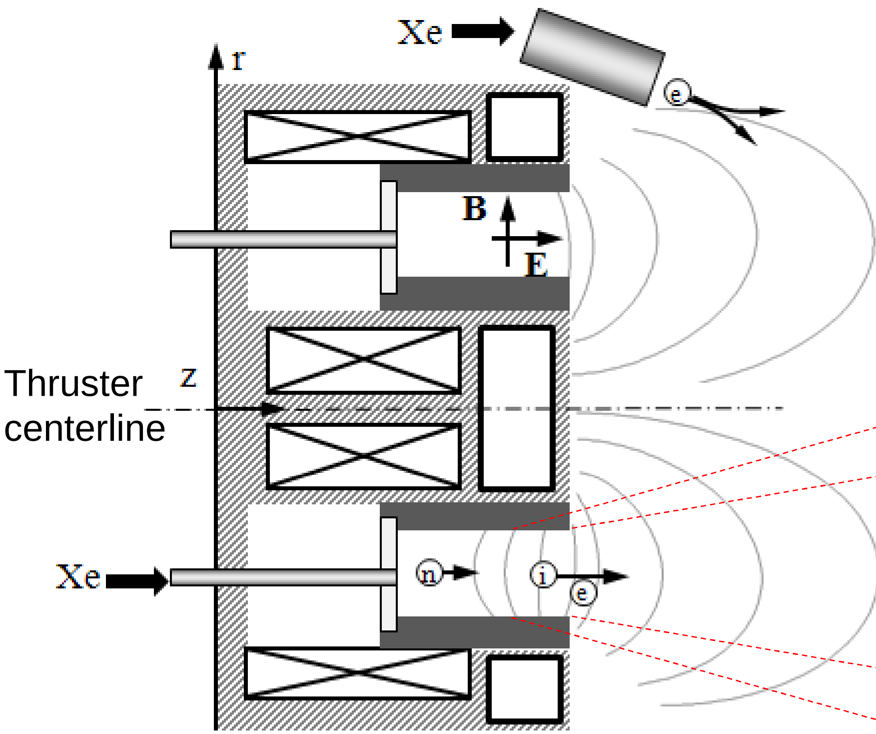
Hall Thruster Physics

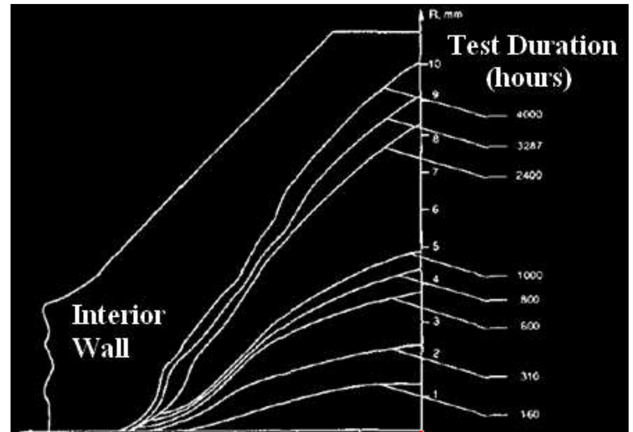


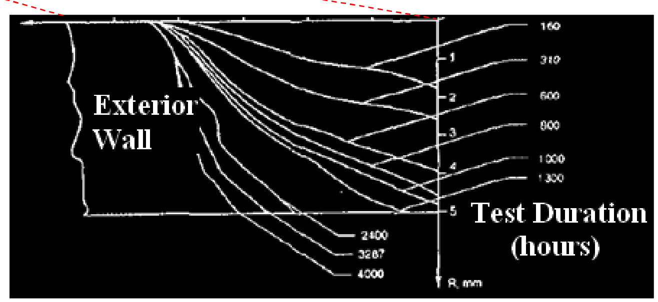


- **Hall thrusters produce a high-energy ion beam using crossed electric (E) and applied magnetic (B) fields.**
  - **E**×**B** motion of electrons dominates drift alone **E**,
  - non-magnetized ions free to accelerate axially to high energy by component of **E** ⊥ to **B** according to Ohm's law.

Erosion in Hall Thrusters







- **Some ions in the beam strike the channel walls with high energy and erode the acceleration channel.**

Erosion physics in Hall thrusters involve plasma-material interactions at multiple scales.

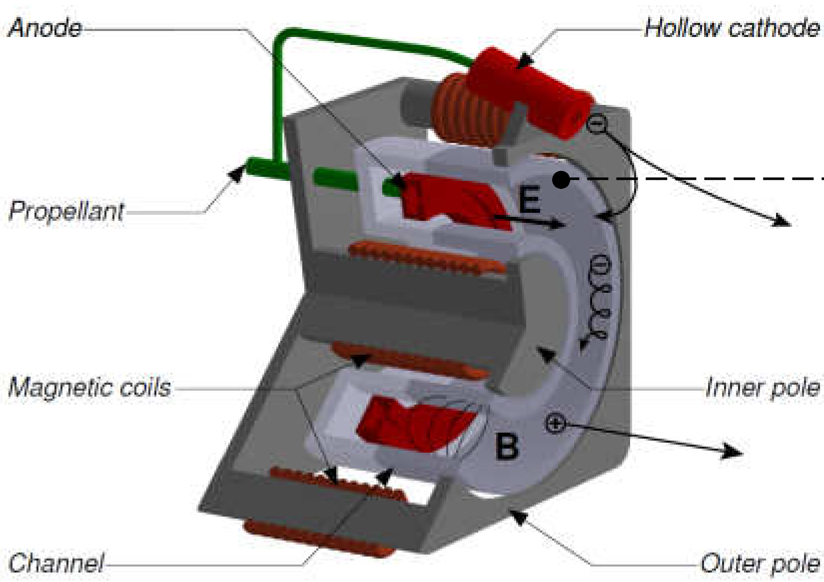
Erosion rate: $\varepsilon = J_\perp Y$

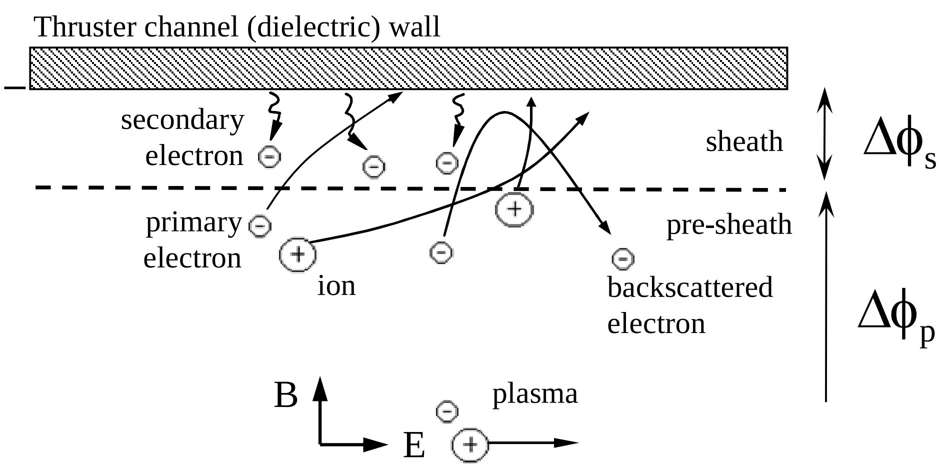
Incident ion current density: $J_\perp = J_\perp\left(n_i, \Delta\phi_p\right)$

Material sputtering yield: $Y = Y\left(K_p + K_s, \theta\right)$

Incident ion kinetic energy gained by acceleration in the plasma: $K_p = K_p\left(\Delta\phi_p\right)$

Incident ion kinetic energy gained by acceleration in the sheath: $K_s = K_s\left(\Delta\phi_s\right), \quad \Delta\phi_s = \Delta\phi_s\left(T_e\right)$





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Background and Motivation (I)

- 1960s-90s: Propulsive performance drives early development of Hall thrusters. Channel erosion recognized as a potentially critical limitation.
  - "*…at the beginning of the 1960s magnetic-force-line equipotentialization became known, and the chosen geometry of force lines (convex toward the anode) provided repulsion of ions from the walls by the electric field, thus reducing the channel erosion*."

    [A. I. Morozov and V. V. Savelyev, *Reviews of Plasma Physics*, 21, 203 (2000)].
  - More than 50 SPT-70s fly in near-earth orbit.

- 1990s-mid 2000s: Significant improvements in performance and life achieved through decades of research.
  - Flight of Hall thrusters for near-earth missions continues.
  - Channel erosion not eliminated or reduced sufficiently to retire the risk for deep-space science missions. Hall thrusters never flown onboard NASA spacecraft.

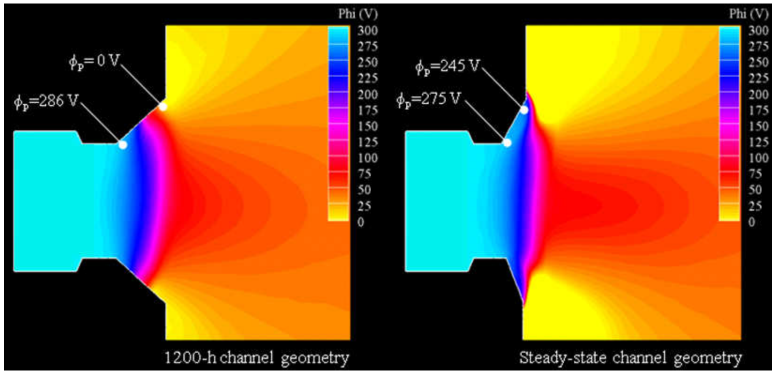
- 2005-2010: A life test of Aerojet's BPT-4000 is extended to >10,000 h [K. de Grys, A. Mathers, B. Welander, V. Khayms, AIAA-2010-6698].
  - For at least the first few thousand hours erosion of the channel insulators occurred typically but then diminished, reaching a near-steady state after ~5,600 h.
  - Implications immense for NASA missions but detailed physics that led to this result unclear.

Background and Motivation (II)

- 2008-2009: New Hall thruster code dubbed "Hall2De" developed to investigate plasma & erosion physics within complicated magnetic field topologies.

- 2009-2010: Hall2De numerical simulations
  – provide explanations of the BPT-4000 test results,
  – propose a technique dubbed "magnetic shielding" to reduce erosion in Hall thrusters by several orders of magnitude.

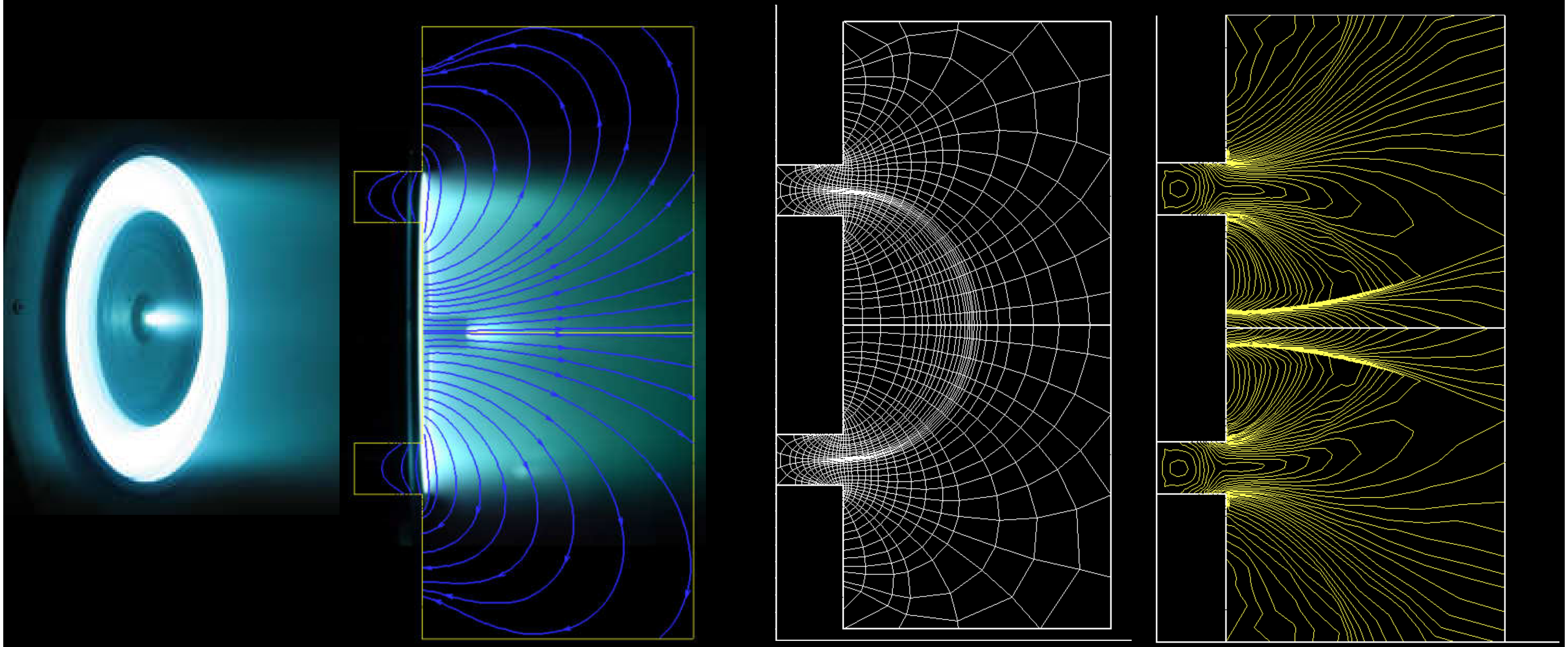
Hall2De simulations of the BPT-4000



- 2010-present: Modifications and testing of an existing laboratory Hall thruster begin at JPL as part of a proof-of-principle effort to
  – validate understanding of magnetic shielding physics,
  – demonstrate ability to design Hall thrusters with at least order-of-magnitude increase in life over the SOA.

Hall2De is a physics-based plasma and erosion solver that began development at JPL in 2008 to assess the life capability of existing Hall thrusters and to guide the design of new long-life thrusters for NASA science missions.

- Discretization of all conservation laws on a magnetic field-aligned mesh
- Two components of the electron current density field accounted for in Ohm's law
- No statistical noise in the numerical solution of the heavy-species conservation laws
- Multiple ion populations allowed
- Large computational domain, extending several times the thruster channel length



6 kW Lab Hall thruster | Magnetic field streamlines | Hall2De computational mesh | Ion density line contours

Physics-based Modeling & Simulation (M&S) Capabilities at JPL Support a Wide Range of NASA Electric Propulsion Technologies

THE MISSION OF THE M&S PROGRAM AT JPL HAS BOTH A NEAR-TERM AND A LONG-TERM IMPACT FOR EP:

- **To Understand Critical Physics**

  that cannot be resolved or accessed by conventional diagnostics, leading to better-performing, longer-life engines
  - example: erosion in ion engine grid apertures
  - example: erosion of the hollow cathode orifice
- **To Discover or Identify Unknown Physics**

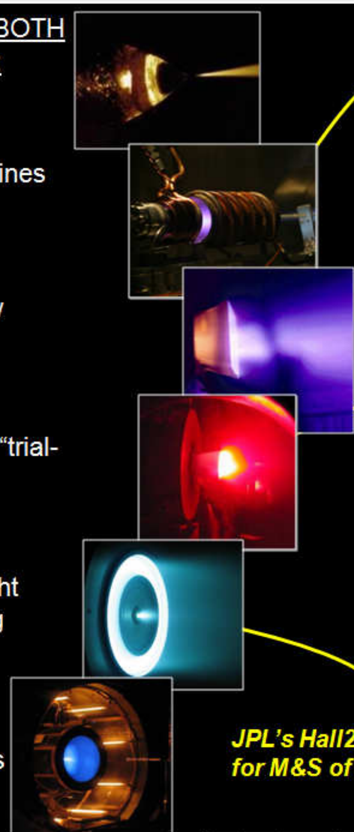
  that may lead to breakthrough capabilities, enabling new science missions for NASA
  - example: "magnetic shielding" in Hall-effect thrusters
- **To Guide Designs**

  of new engines (or refine past designs), reducing costly "trial-and-error" tests
  - example: NEXIS ion optics
- **To Diminish Risk**

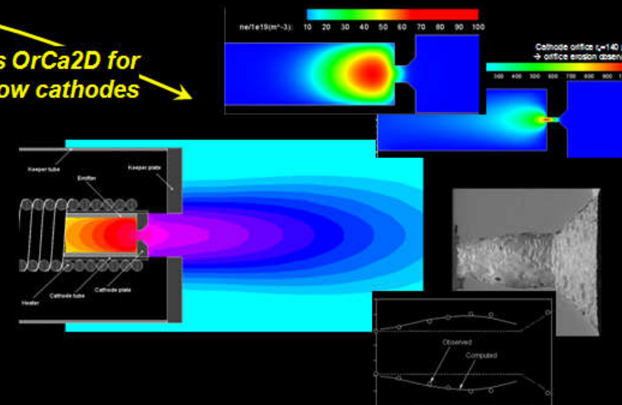
  - both real and perceived - by elucidating test and/or flight observations that are not well understood and publishing findings in peer-reviewed journals
- **To Reduce Qualification Costs**

  by verifying performance and/or life capability that is otherwise too costly to demonstrate by qualification tests
- **To Shorten Time To Flight**

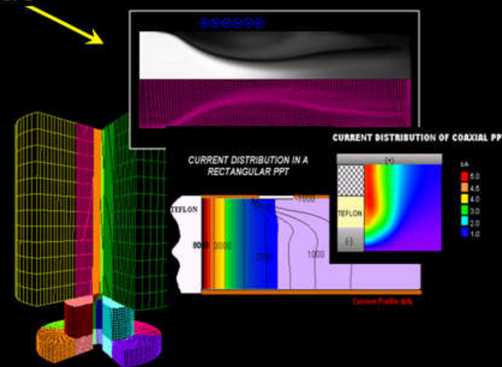
  by reducing time to qualify



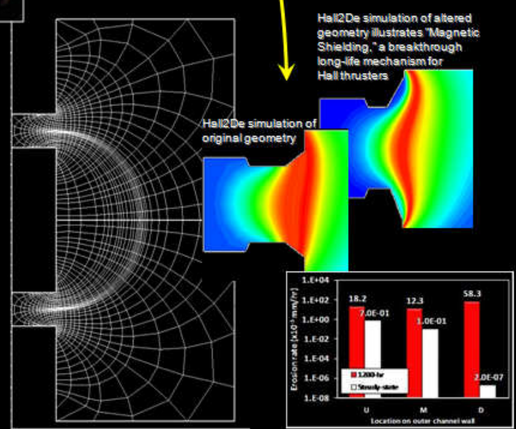
JPL's OrCa2D for M&S of EP hollow cathodes



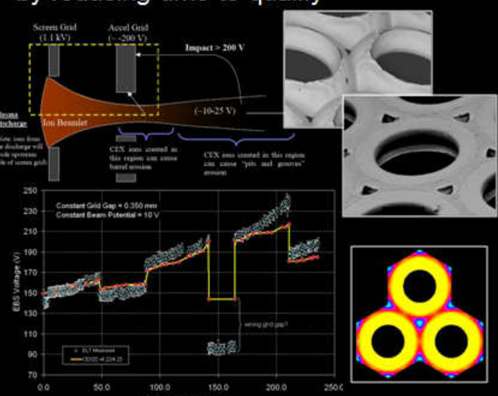
AFRL's MACH 2D & 3D resistive-Hall MHD codes for M&S of a variety of pulsed and steady-state electromagnetic thrusters



JPL's Hall2De & MIT/AFRL's HPHall for M&S of Hall-effect thrusters



JPL's CEX 2D & 3D for M&S of ion engine optics



Strong university partnerships strengthen and expand our in-house M&S capabilities.

- **UCI, Caltech: fundamental processes in colloid microthrusters**
- **ASU: MHD processes in electromagnetic propulsion and high-performance computing**
- **UCLA: fundamental plasma physics in ion engine discharge chambers**

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A proof-of-principle effort began at JPL in 2009 to demonstrate magnetic shielding can “eliminate” channel erosion in Hall thrusters.

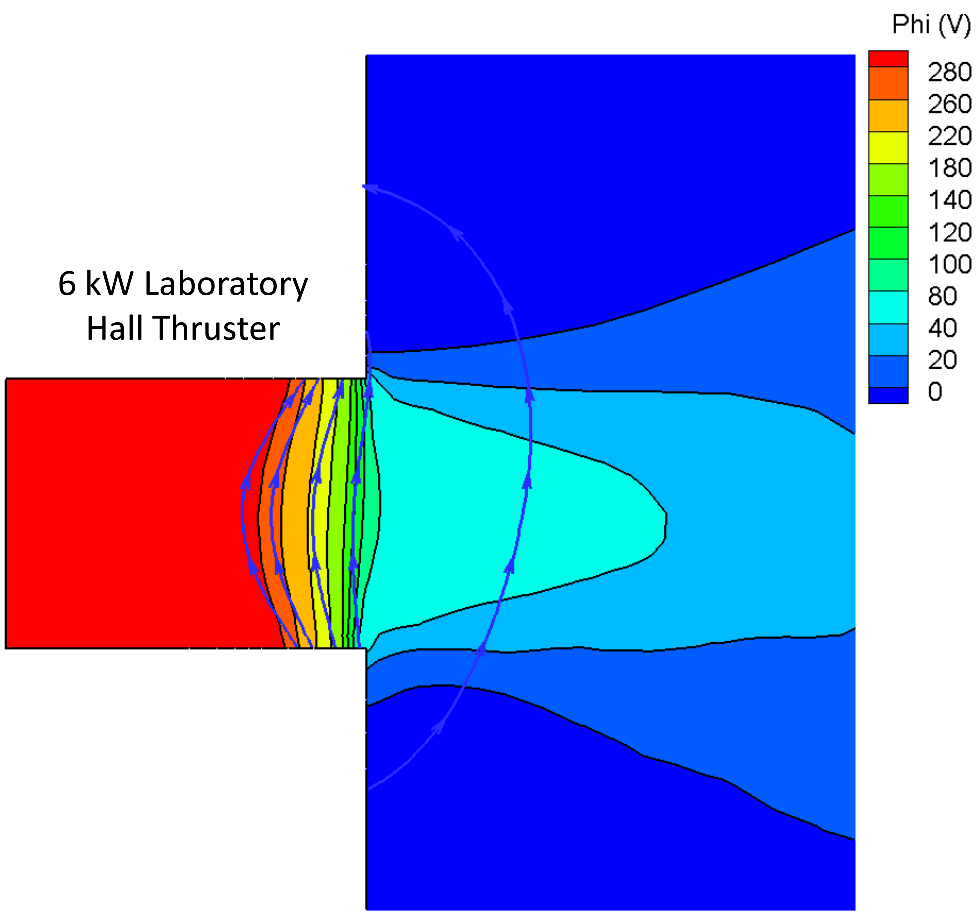
- 2-yr research and technology development (R&TD) program funded by JPL
  - Principal Investigator: Mikellides, I.
  - Co-Investigators: Katz, I., Hofer, R. and Goebel, D.

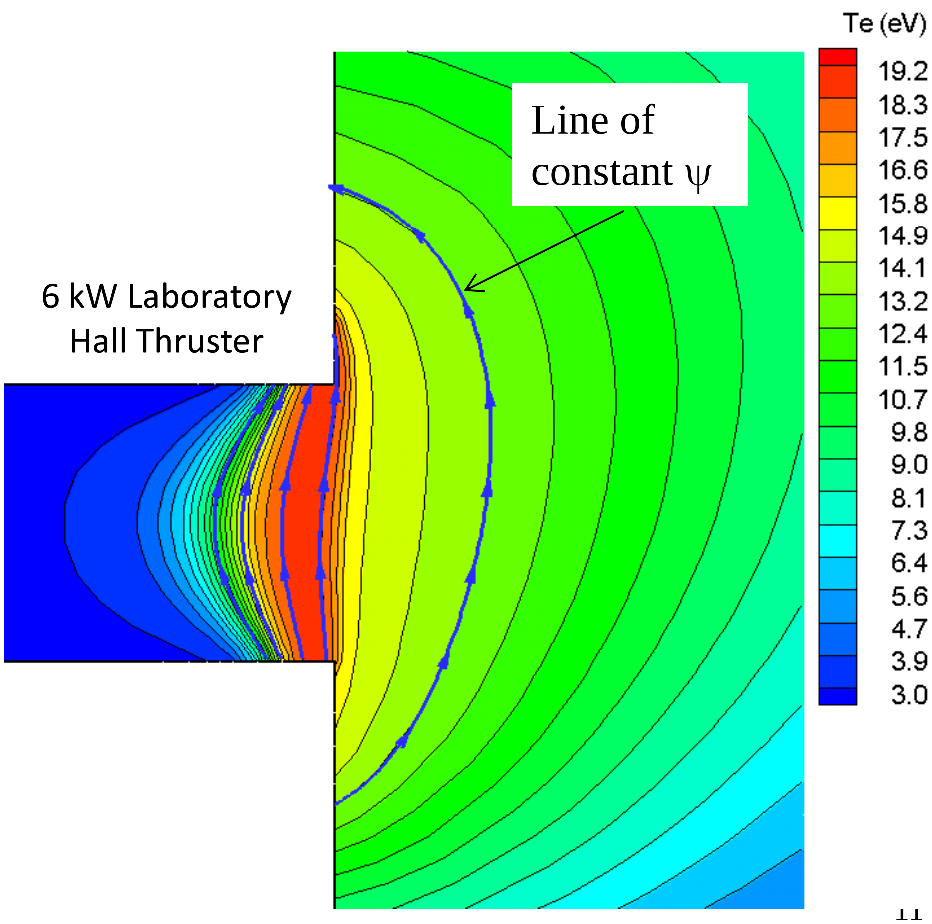
- Neither theory nor experiment alone can validate fully the first principles of magnetic shielding. The objective of the 2-yr effort was therefore twofold:
  - *to demonstrate in the laboratory that erosion rates can be reduced by >2 orders of magnitude and,*
  - *to demonstrate understanding of the theory that enables such reductions in the erosion rates.*

The “Equipotentialization” and “Isothermalization” of the lines of force are well-known features of Hall thrusters.

$$\Omega_e^2 >> 1: \qquad \nabla_{\parallel} T_e \approx 0 \qquad \frac{\nabla_{\parallel} p_e}{e n_e} - \nabla_{\parallel} \phi \approx 0$$

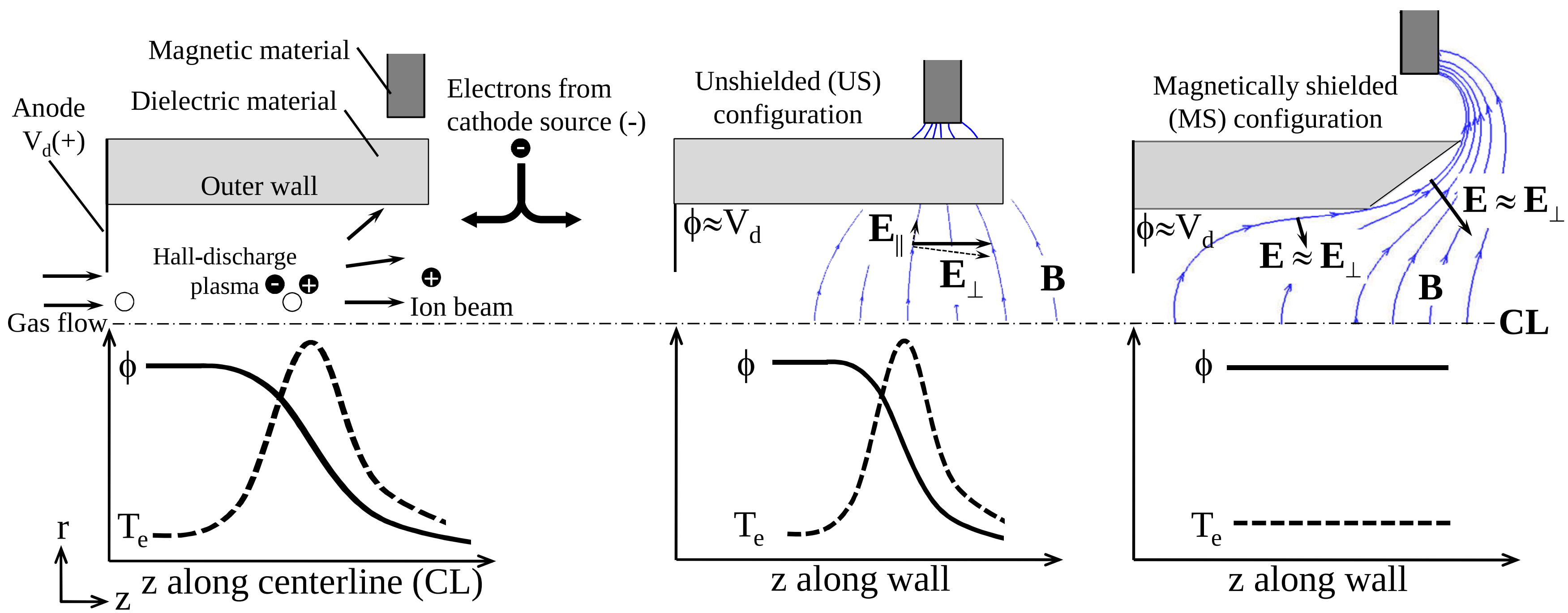
$$\boxed{T_e(\psi) \approx \text{const.} \qquad \phi(\psi) - T_e(\psi)\ell n[n_e(\psi)] \approx \text{const. (the "Thermalized potential")}}$$



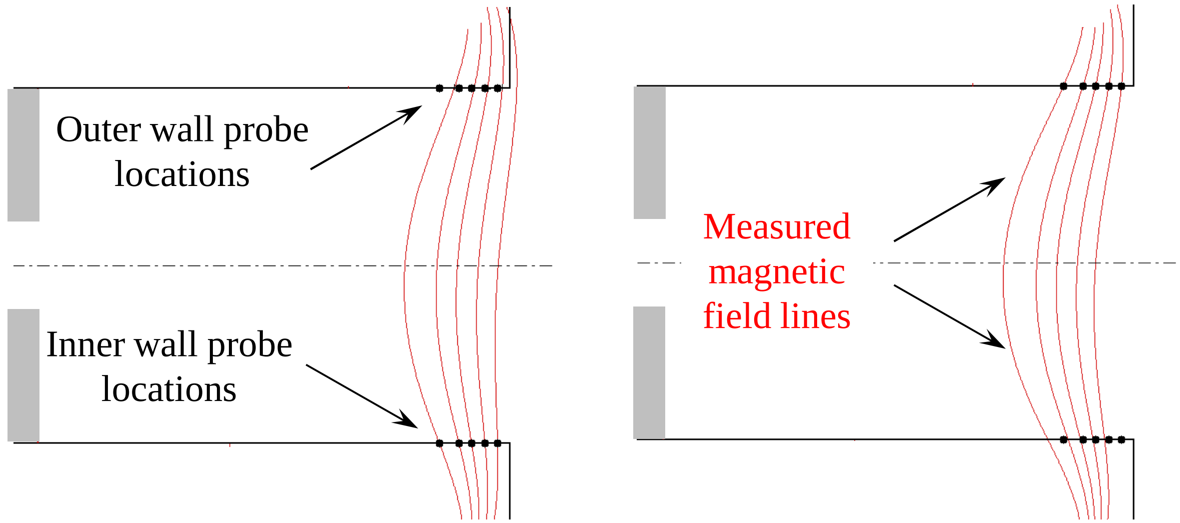


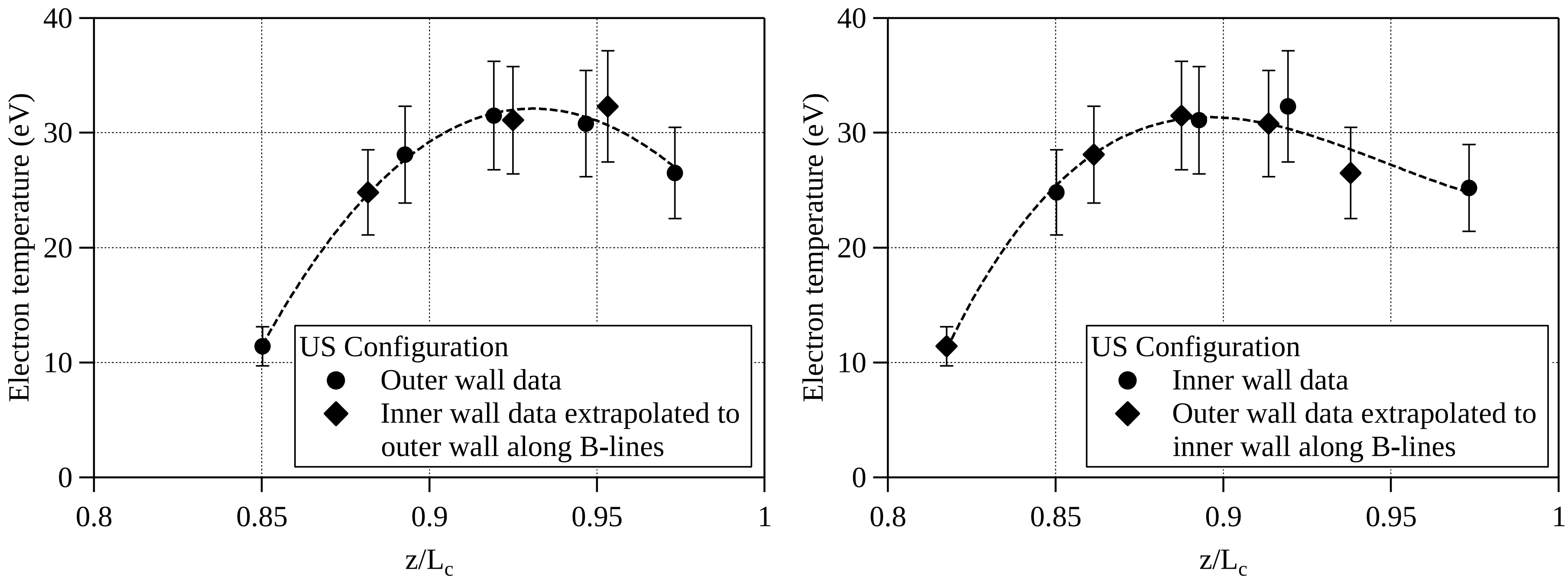
Magnetic Shielding First Principles

- What does it do? It achieves adjacent to channel surfaces:
  - high plasma potential
  - low electron temperature
- How does it do it? It exploits magnetic field lines that extend deep into the acceleration channel, which marginalizes the effect of $T_e \times \ln(n_e)$.
- Why does it work? It reduces significantly ALL contributions to erosion: ion kinetic energy, sheath energy and particle flux.



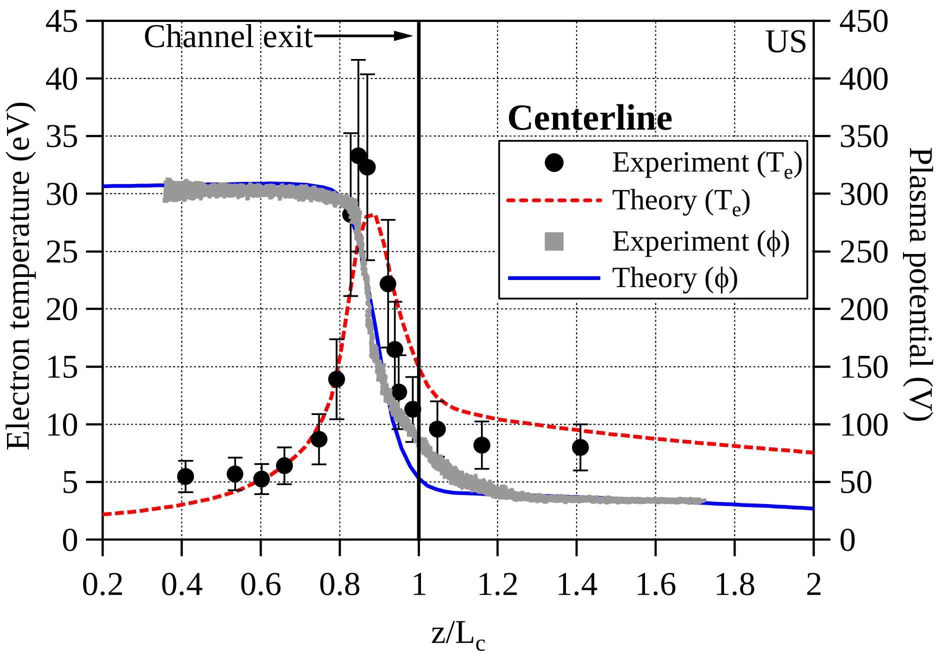
Direct measurements provide strong evidence that the lines of force are indeed isothermal.

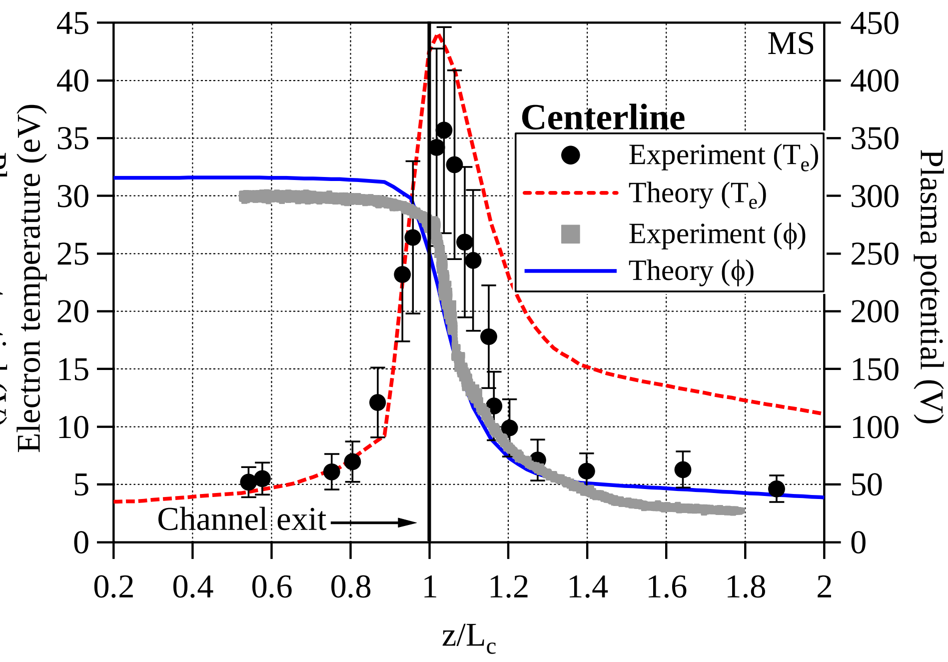




Comparisons of Plasma Properties Along the Channel Centerline
- Plasma Potential & Electron Temperature -

- Plasma measurements for ϕ and T_e guide non-classical collision frequency in both configurations.
- Distance between ϕ & T_e maxima in the two configurations approximately equal to the distance between magnetic field maxima at the centerline.
- Discrepancies in the near-plume of the MS configuration of little significance to wall erosion.





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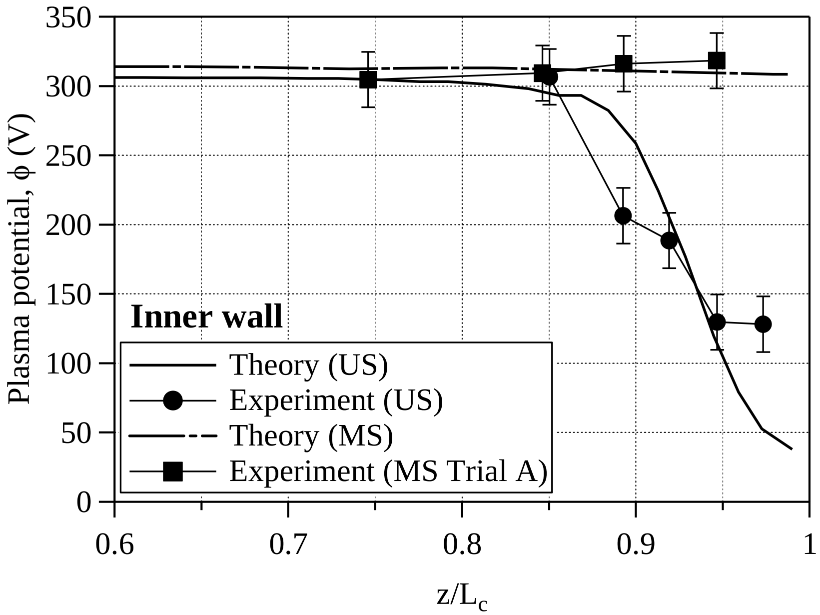
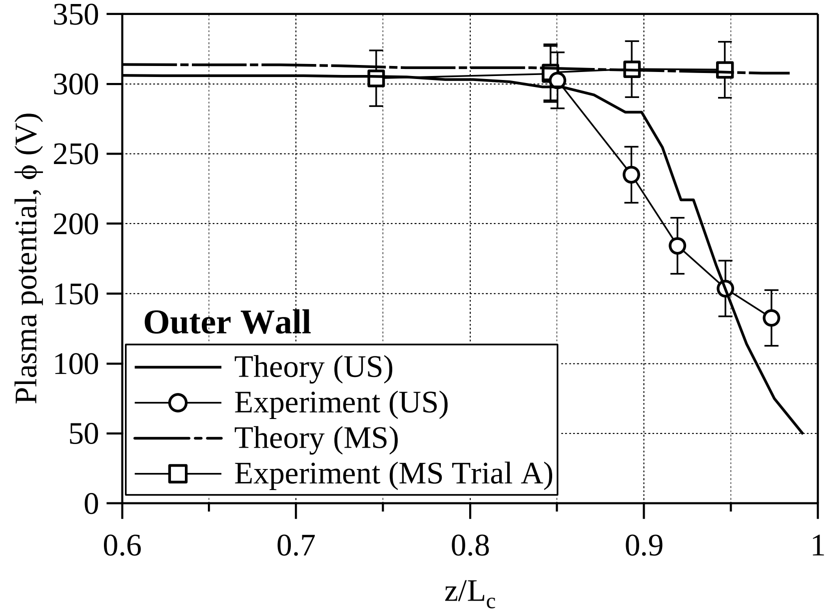
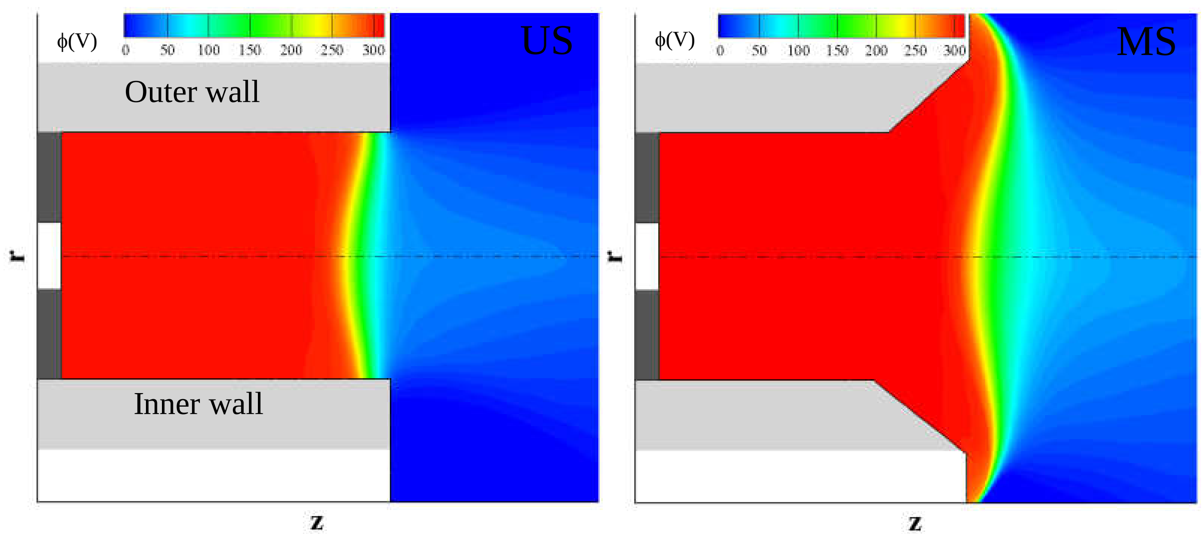
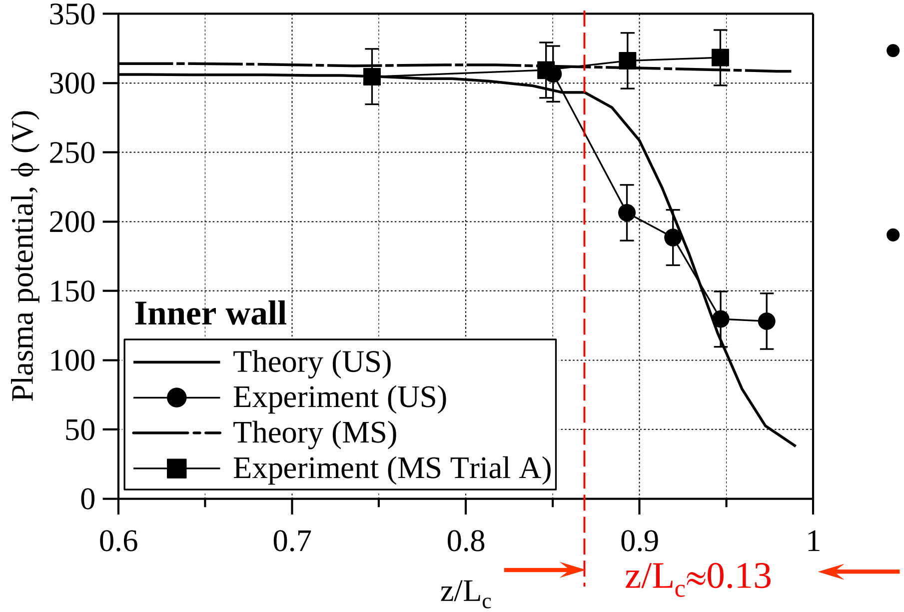
Comparisons of Plasma Properties Along the Channel Walls - Plasma Potential -







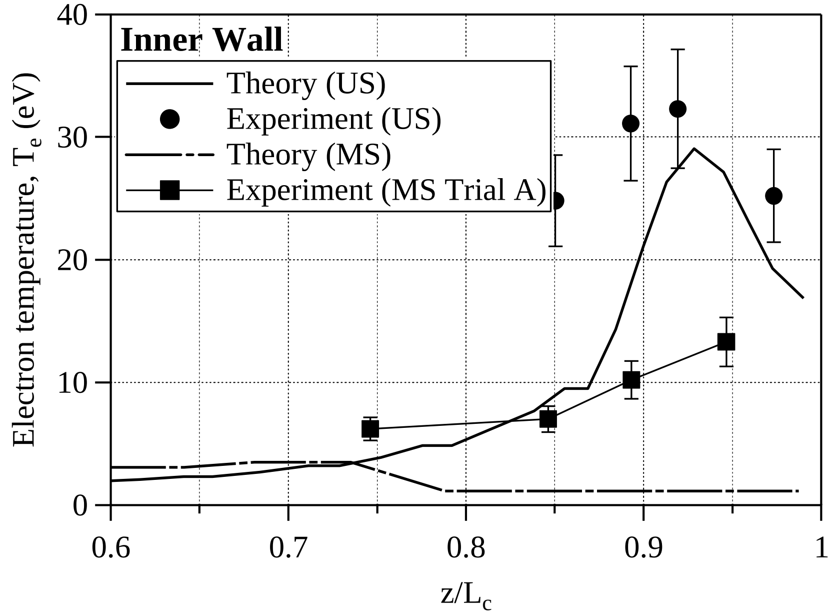
Comparisons of Plasma Properties Along the Channel Walls - Plasma Potential at the Inner Wall-

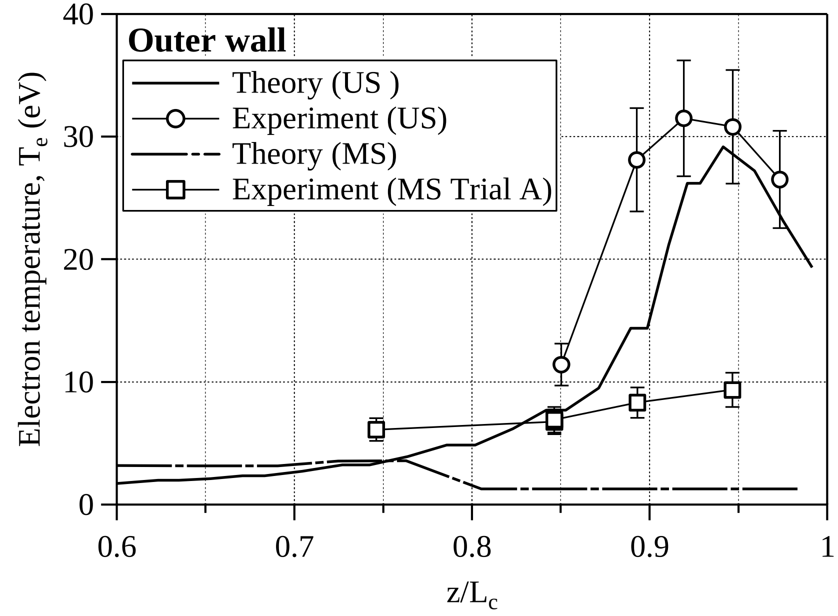


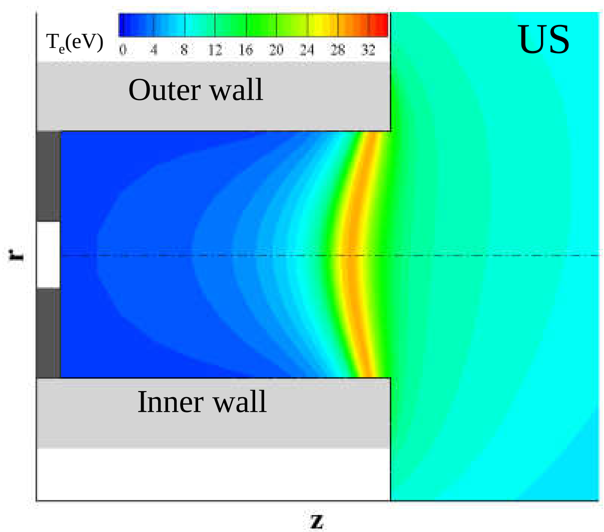
- "Erosion band" clearly visible in the US configuration and consistent with wall probe data and simulations.
- No "erosion band" in the MS configuration
  - some discoloration in the last 3% of Trial-A test
  - fully coated with carbon when the test was repeated in Trial B.

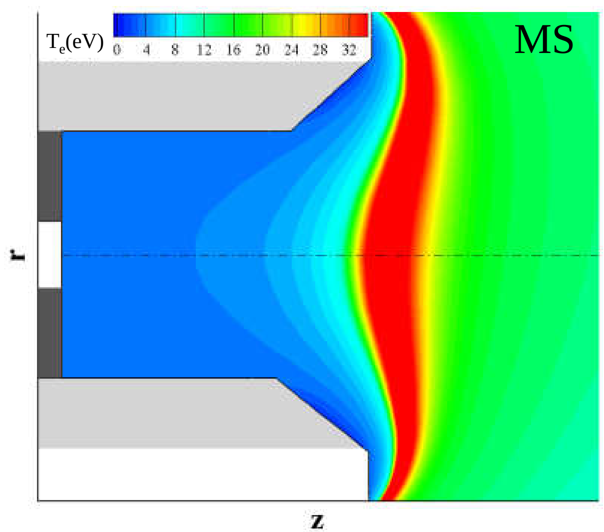
Inner US ring **Inner MS ring**

Comparisons of Plasma Properties Along the Channel Walls
- Electron Temperature -

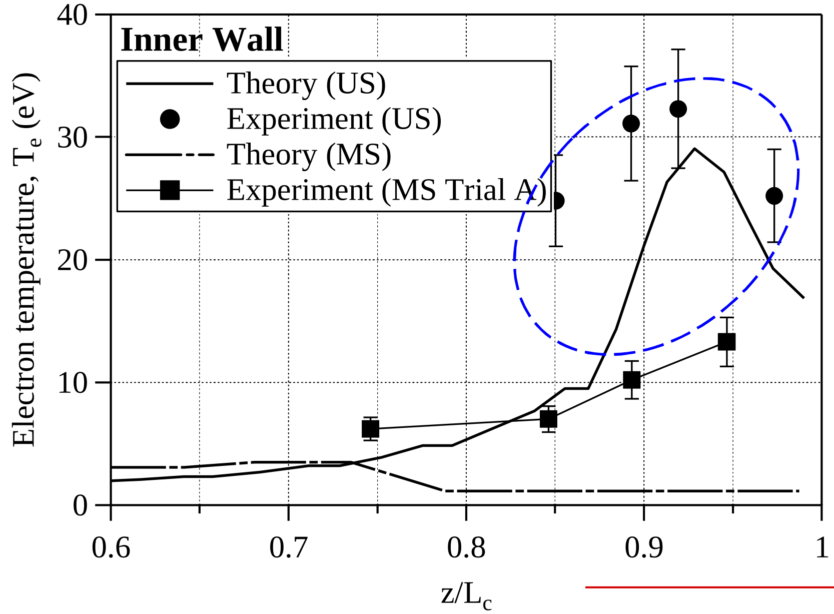


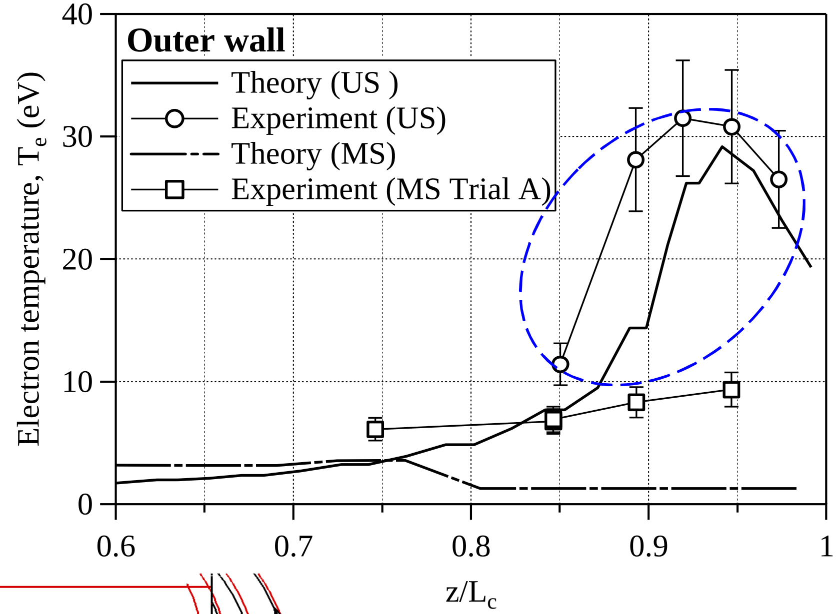


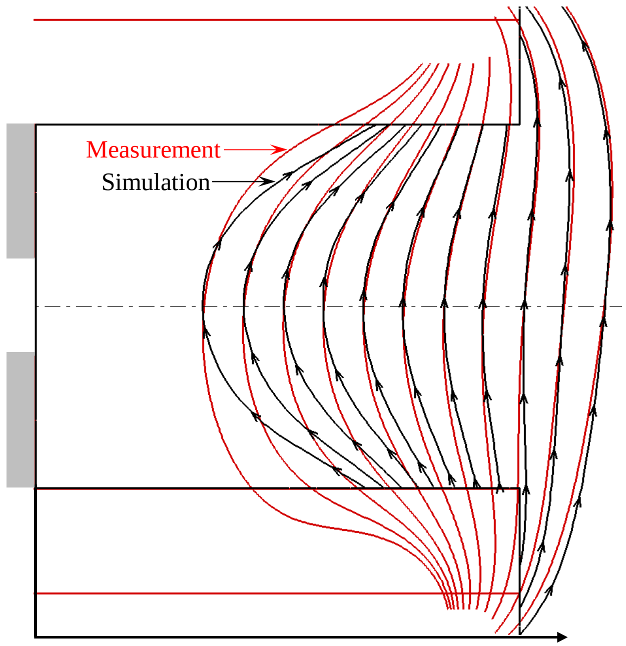




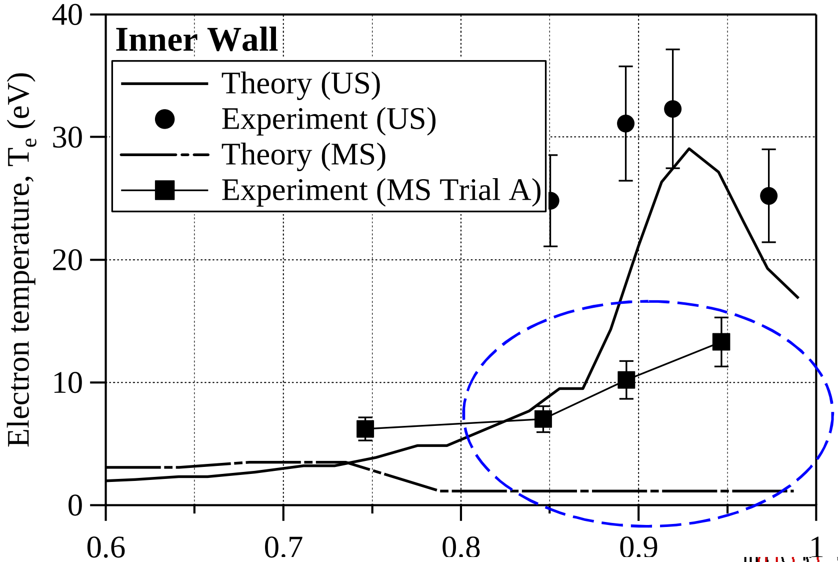
Comparisons of Plasma Properties Along the Channel Walls - Electron Temperature in the US Configuration-

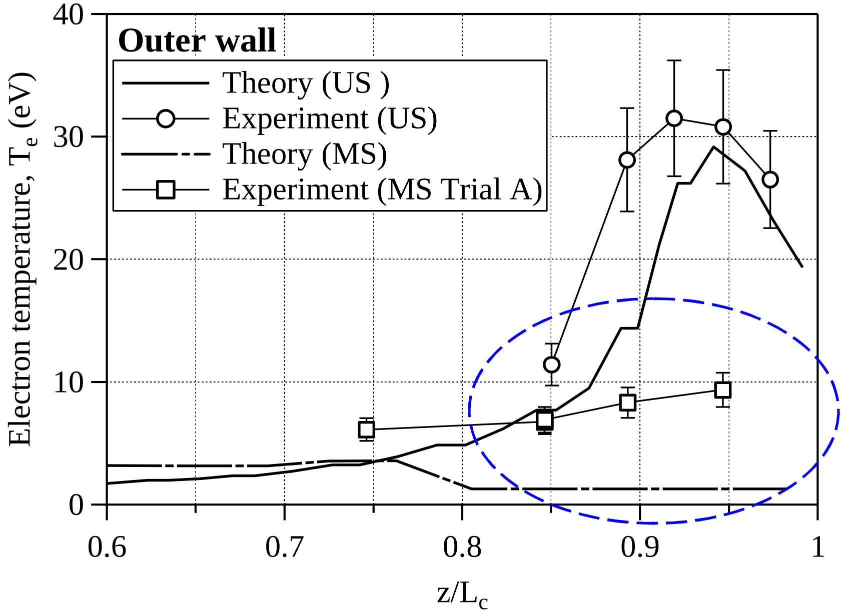


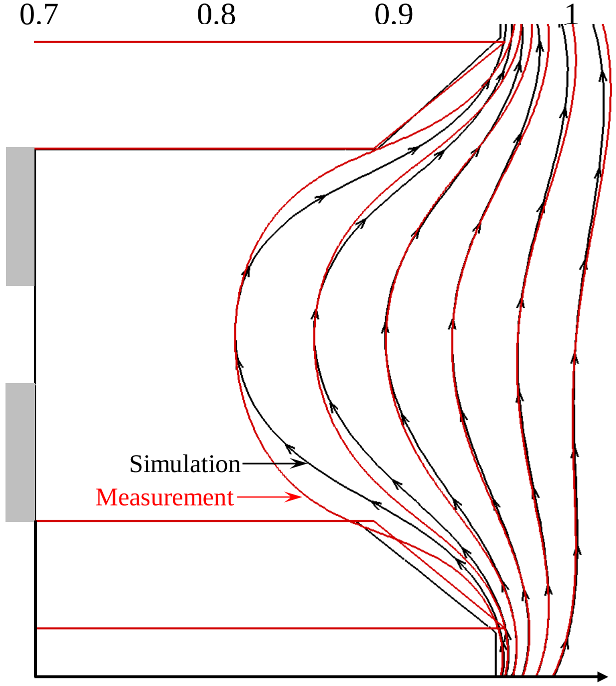


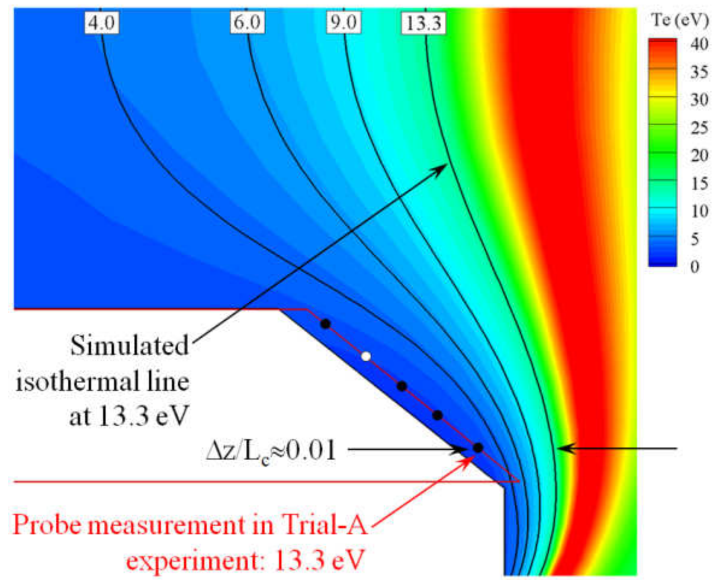


Comparisons of Plasma Properties Along the Channel Walls - Electron Temperature in the MS Configuration -









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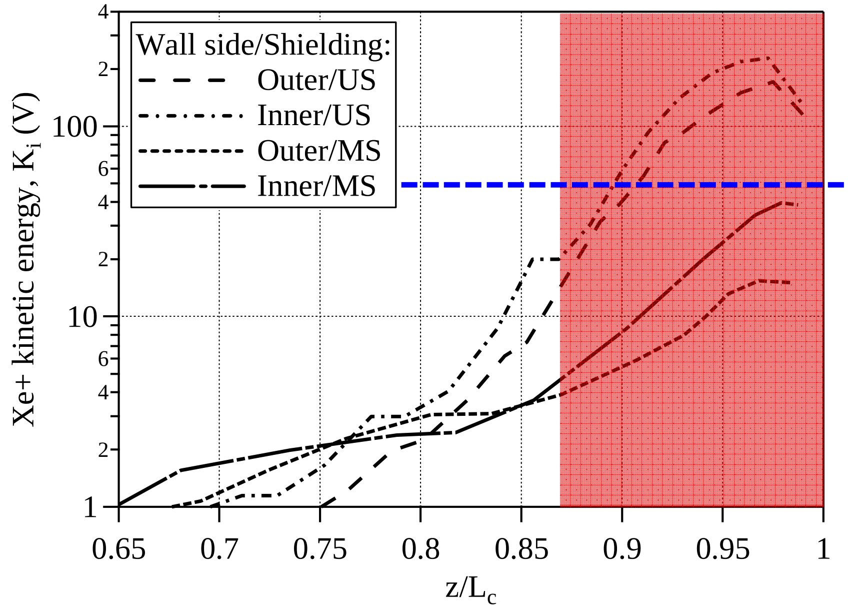
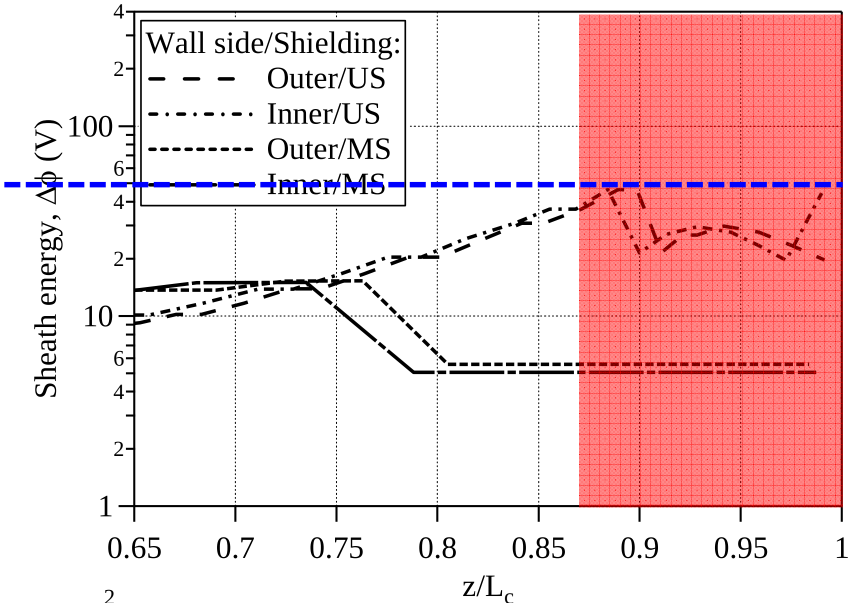
Kinetic energy gained by ions in the plasma dominates contributions to erosion over sheath energy → Differences between measured & simulated T_e of no major significance to erosion.





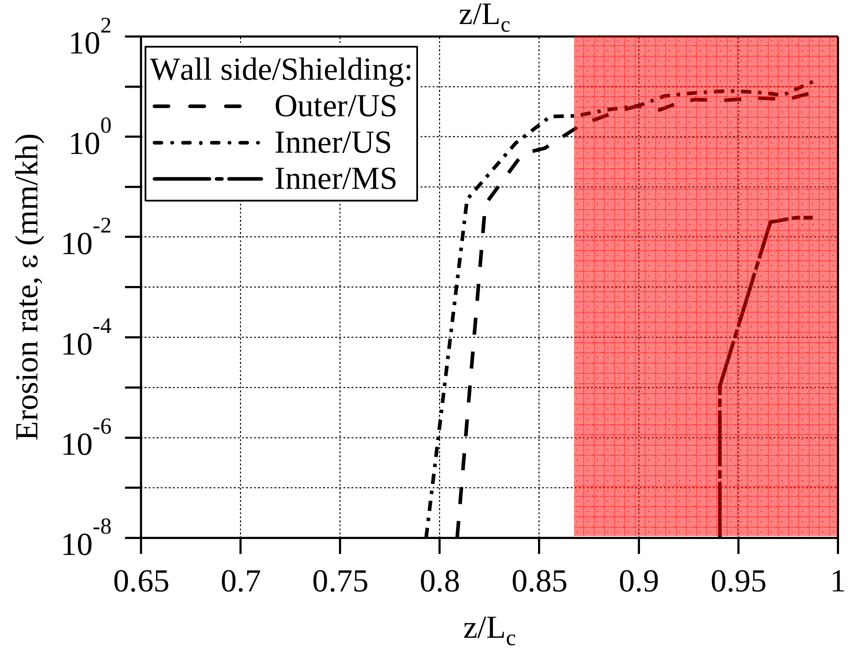
Erosion rate $\varepsilon = J_\perp Y$

Incident current density $J_\perp = J_\perp(n_i, \Delta\phi_i)$

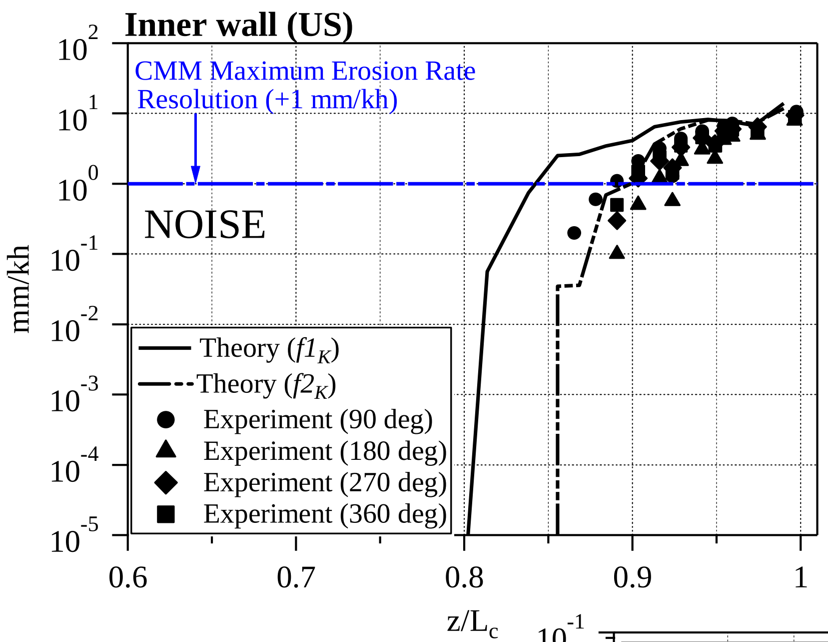
Sputtering yield $Y = Y(K_i + K_s, \theta)$

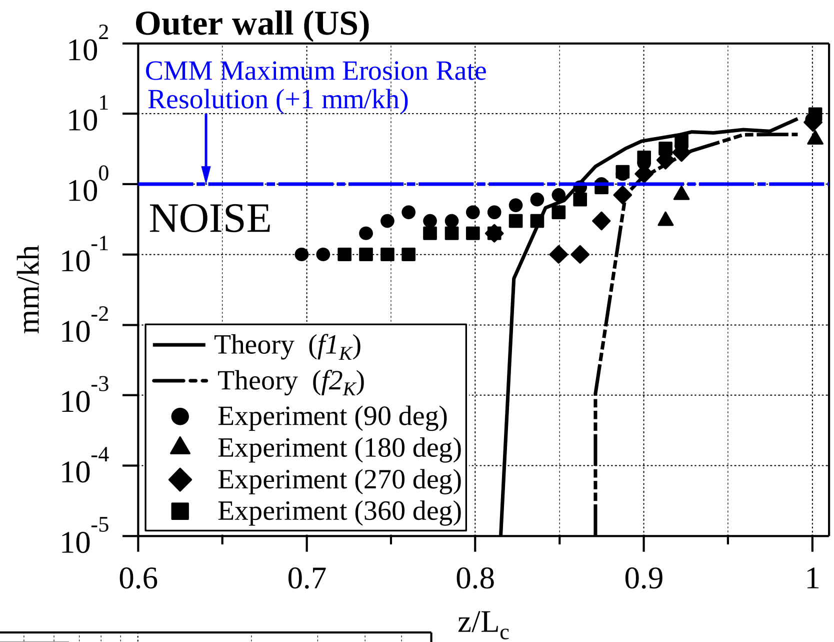
Ion kinetic energy $K_i = K_i(\Delta\phi_i)$

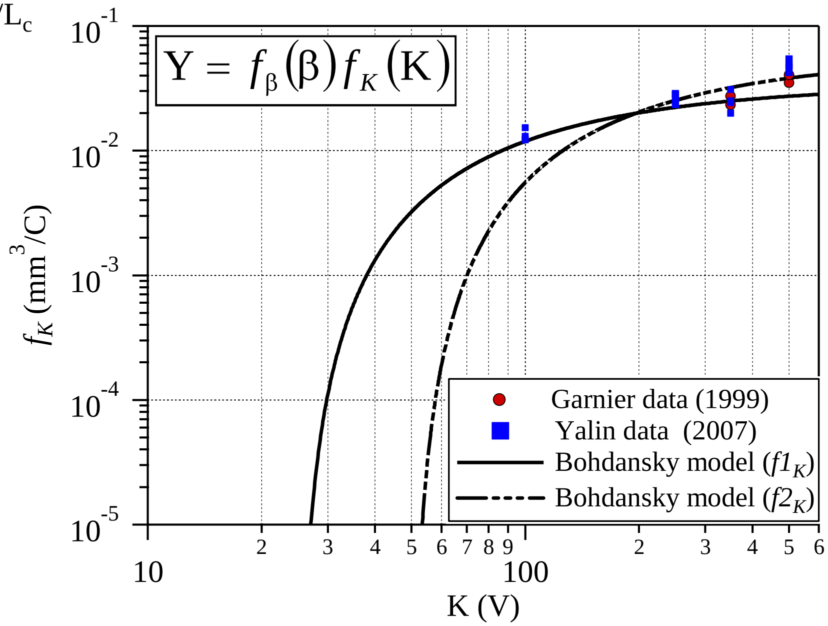
Ion sheath energy $K_s = K_s(\Delta\phi_s), \quad \Delta\phi_s = \Delta\phi_s(T_e)$



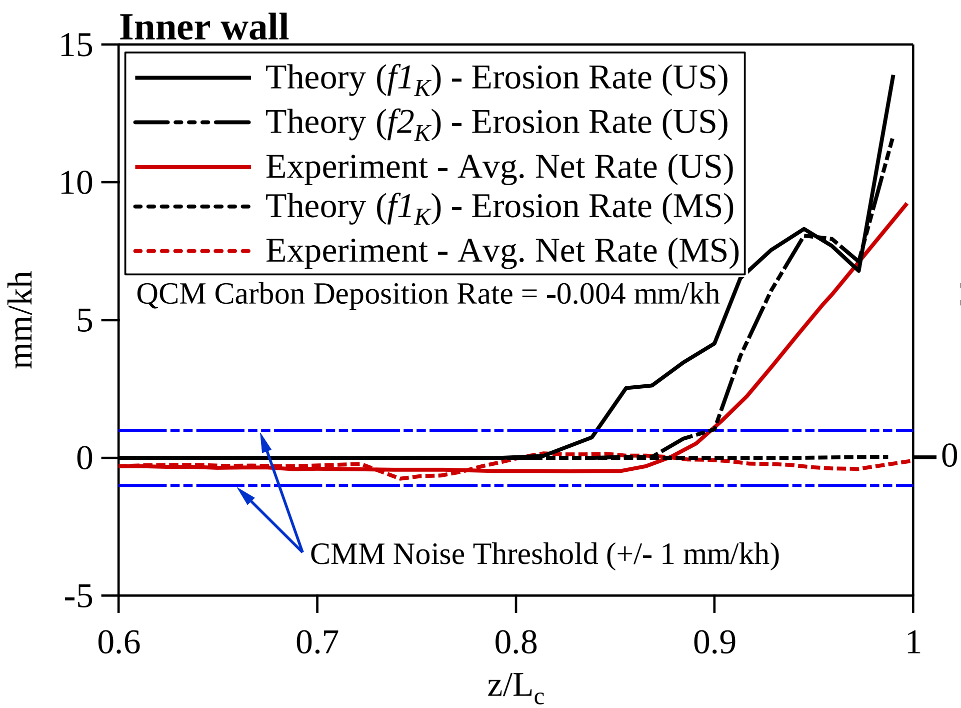
Comparisons of Erosion Rates Along the Channel Walls - US Configuration -

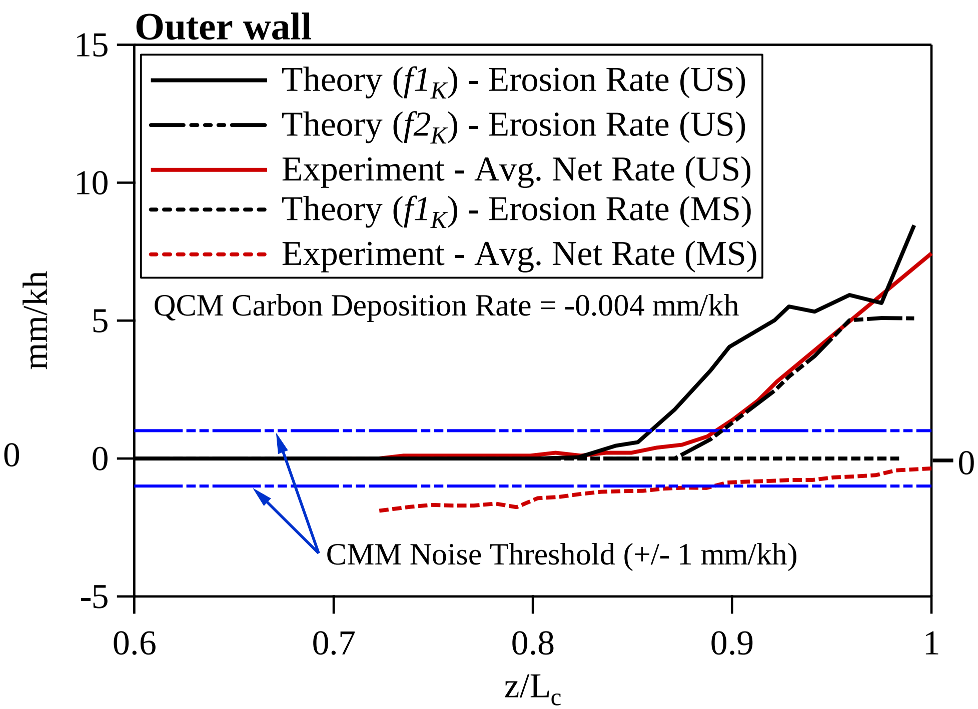






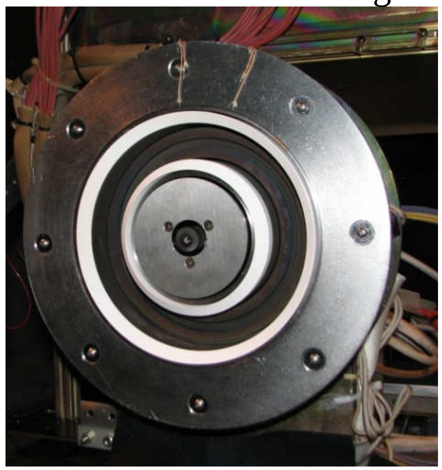
Comparisons of Erosion Rates Along the Channel Walls - US & MS Configurations -





Summary of Comparisons on Minimum Erosion Rate Reductions

H6MS before testing



H6MS after 15 h of testing

	THEORY		EXPERIMENT (Trial A)	
	$\varepsilon_{US}/\varepsilon_{MS}$	Notes	$\varepsilon_{US}/\varepsilon_{MS}$	Notes
Inner wall	~600 to ∞	K_T=25 to 50 V (Bohdansky $f1_K$ & $f2_K$ models)	~1000	(1) Based on wall probes (2) K_T=30.5 V (Bohdansky $f3_K$ model)
			Unknown to $\gtrsim$2000	Based on QCM deposition rates
Outer wall	∞	Ion energy <K_T=25 V (Bohdansky $f1_K$ model)	∞	(1) Based on wall probes (2) Ion energy <K_T=30.5 V (Bohdansky $f3_K$ model)
			Unknown to $\gtrsim$2000	Based on QCM deposition rates

Magnetically Shielding Reduces Erosion by Orders of Magnitude Without Degrading Thruster Performance.

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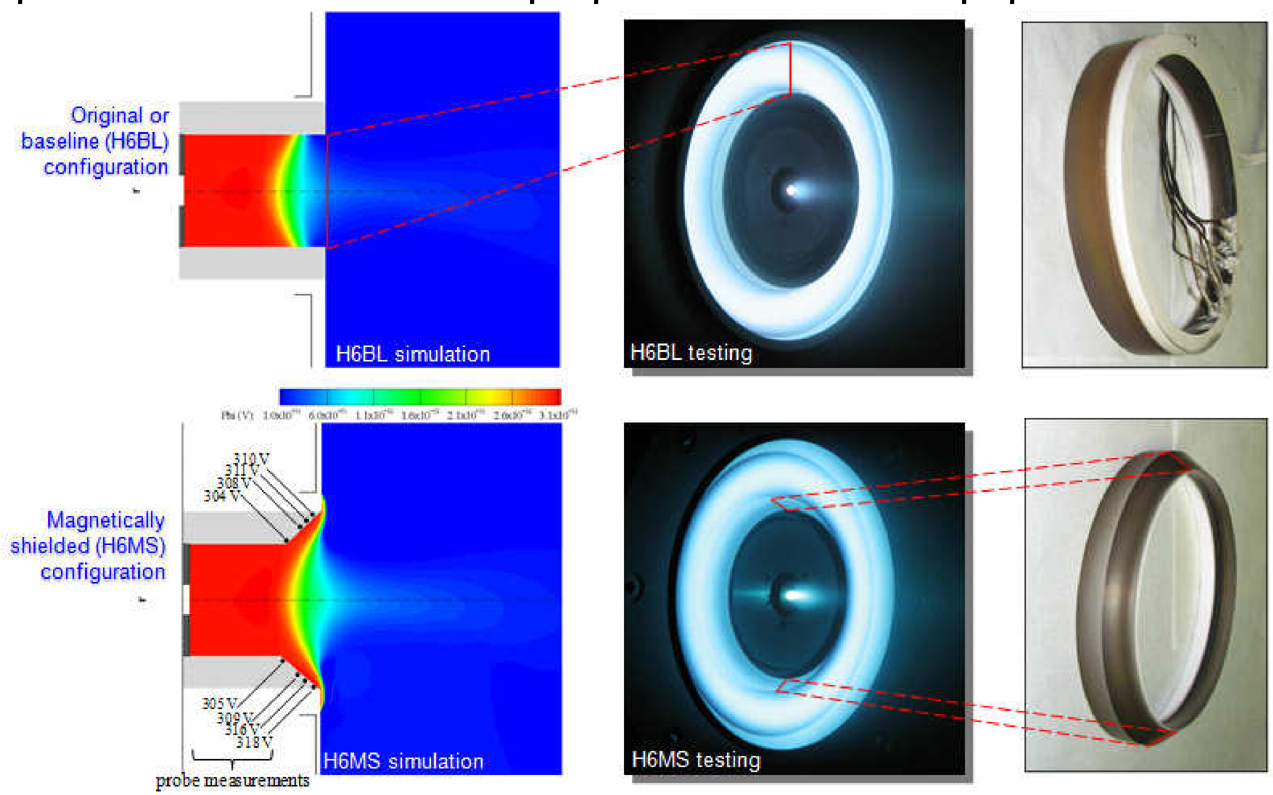
Modeling & simulations guide MS thruster design

Thruster testing performed to validate MS

Plasma and erosion diagnostics confirm MS with only small changes in performance



- Thrust: 401 mN
- Specific Impulse: 1950 s
- Efficiency: 63.5%

- Thrust: 385 mN
- Specific Impulse: 2000 s
- Efficiency: 62.6%

Summary Remarks

- Collectively, the comparisons between simulations and measurements provide strong evidence that the first principles of magnetic shielding are now well understood and can be applied to reduce erosion in Hall thrusters by at least 2 orders of magnitude.

- Uncertainties and discrepancies exposed by the comparisons do not appear to alter the effectiveness of magnetic shielding.

- These findings have significant and immediate implications on science missions. The elimination of wall erosion in Hall thruster solves a problem that has remained unsettled for several decades, allowing for new space exploration missions that could not be undertaken in the past.

Publications and New Technology Reports (NTR) on Magnetic Shielding in Hall Thrusters

1) Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Magnetic Shielding of Walls from the Unmagnetized Ion Beam in a Hall Discharge," *Applied Physics Letters*, in preparation.
2) Mikellides, I. G., and Katz, I., "Simulation of Hall-effect Plasma Accelerators on a Magnetic-field-aligned Mesh," accepted for publication in the *Physical Review E*, July 2012.
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